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Life cycle assessment and life cycle costing of bioethanol from sugarcane in Brazil

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ABSTRACT

Brazil has always been the pioneer in the application of bioethanol as a main fuel for automobiles, hence environmental and economic analyses of the Brazilian ethanol industries are of crucial importance. This study presents a comparative life cycle assessment (LCA) on gasoline and ethanol as fuels, and with two types of blends of gasoline with bioethanol, all used in a midsize car. The focus is on a main application in Brazil, sugarcane based ethanol. The results of two cases are presented: base case—bioethanol production from sugarcane and electricity generation from bagasse; future case—bioethanol production from both sugarcane and bagasse and electricity generation from wastes. In both cases sugar is co-produced. The life cycles of fuels include gasoline production, agricultural production of sugarcane, ethanol production, sugar and electricity co-production, blending ethanol with gasoline to produce E10 (10% of ethanol) and E85 (85%), and finally the use of gasoline, E10, E85 and pure ethanol. Furthermore, a life cycle costing (LCC) was conducted to give an indication on fuel economy in both cases. The results show that in the base case less GHG is emitted; while the overall evaluation of these fuel options depends on the importance attached to different impacts. The future case is certainly more economically attractive, which has been the driving force for development in the ethanol industry in Brazil. Nevertheless, the outcomes depend very much on the assumed price for crude oil. In LCC a steady-state cost model was used and only the production cost was taken into account. In the real market the prices of fuels are very much dependent on the taxes and subsidies. Technological development can help in lowering both the environmental impact and the prices of the ethanol fuels.

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1. Introduction

The concept of biofuels, especially bioethanol, has been promoted all over the world, and the rational behind mainly focuses on the reduction of fossil resource use and greenhouse effect. With respect to these two aims the feasibility of bioethanol in terms of environmental impact has been challenged [1–7]. The major outcomes of these studies are the reduction of fossil resource extraction and greenhouse gas (GHG) emissions to some extent. The current technology in industry is able to convert carbohydrates from dedicated crops such as corn, wheat, sorghum, potato, sugarcane, sugar beet and cassava to ethanol [2–4,8–12]. However, the land use requirement of such an application causes the competition with food and nature, which has become the main driving force of the development and implementation of advanced process technologies to produce ethanol from celluloses from low value agricultural co-products or wastes like corn stover, wheat straw, sugarcane bagasse, wood or grass. Several LCA studies focusing on these advanced technologies have been conducted [13–18], concluding a reduction of fossil fuel use and GHG emissions. However, other environmental impacts including land requirements caused by bioethanol production and application received much less attention. Furthermore, economic feasibility has not been of concern in the LCA studies. Hence a study with a complete set of impact categories and an indication of fuel economy is in urgent need.

Since early 1970s Brazil has been the major fuel ethanol producer in the world depending on sugarcane as feedstock. Ethanol from sugarcane with its biorenewable nature and optimized production technology is already proven as a replacement for fossil fuels in Brazil [19]. The advanced process technology has also been developed to produce ethanol from cellulosic feedstock–bagasse. Hence the main research question is raised as ‘Is the 2nd generation bioethanol from sugarcane better than 1st generation?’ To answer this question it is of crucial importance to research on the environmental impact and economic feasibility of sugarcane ethanol as a transport fuel. Here the term ‘2nd generation’ bioethanol means the involvement of using both sucrose and bagasse for ethanol production, unlike the 1st generation bagasse is burned for heat and power generation.

This paper focuses on bioethanol from sugarcane involving the cellulosic technology and a complete set of environmental impacts of importance. The full life cycles of bioethanol and gasoline are analyzed, including the production and transport of raw materials and fuels, the production of equipments and energy in the plant, and the application of fuels. The agriculture and process data based on the local conditions in Brazil are used. The LCA methodology used, especially allocation procedures follows the guidelines described in the *Handbook on Life Cycle Assessment* [20].

2. Methodology

Life cycle assessment (LCA) is a method for determining the environmental impact of a product (good or service) during its entire life cycle—from extraction of raw materials through manufacturing, logistics and use to scrapping and recycling. In LCA substantially broader environmental aspects can be covered, ranging from GHG emissions and fossil resource depletion to acidification and toxicity aspects, hence it is a good tool for quantifying environmental impacts of a defined product system. However, LCA as it stands has its limitations such as the difficulties in data acquisition and validation, and the misleading results due to the choice of methodology especially on allocation issues.

Life cycle costing (LCC) is a process to determine the sum of all the costs associated with an asset or part thereof, including acquisition, installation, operation, maintenance, and refurbishment and disposal costs. In LCC a steady-state cost model is engaged, and only production cost is taken into account, thus it cannot be used to model the dynamics in the markets.

The present study concerns the comparison of technologies and costs for the car driving function, with Brazilian local circumstances playing a role. Not only was the comparison between driving on gasoline and ethanol fuels made, but also the one between ethanol from two processes involving different technologies was made. The two cases engaged are: base case—bioethanol production from sucrose, and heat and electricity generation from bagasse using the current technology; future case—bioethanol production from both sucrose and bagasse, and heat and electricity generation from wastes. In the process of ethanol from bagasse advanced technology was assumed, meaning that genetically modified organism (GMO) is used to ferment both C5 and C6 sugar to increase the yield. In both cases sugar is co-produced. The following issues are of specific interest.

2.1. Functional unit and alternatives

The functional unit in this study is defined as power to wheels for 1 km driving of a midsize car. Not the full car is taken into account but only its energy requirements in driving. In practice, ethanol is mainly used in one of two ways in vehicle fuel [21,22]: (1) blended with gasoline, typically 5–20% by volume, for use in existing vehicles with no engine modifications; (2) blended with gasoline, typically 85-100% by volume, for use in vehicles with specifically modified engines. In this study ethanol is assumed to be used in both ways, as a mixture of 10% ethanol with 90% gasoline by volume (termed E10), and as a mixture of 85% ethanol with 15% gasoline by volume (termed E85). As a reference alternative, a hypothetical case of 100% ethanol is also taken into account. Therefore the fuel alternatives are gasoline, E10, E85 and 100% ethanol, in amounts required to deliver the same amount of energy ‘to the wheels’.

2.2. System boundary

All relevant processes are included within the boundary of the fuel systems, including those for capital goods and wastes management. Base case and future case are shown in Figs. 1 and 2, respectively.

In the base case the ethanol production includes sugarcane milling, juice clarification, fermentation and purification of ethanol; as well as the co-production of sugar from sucrose and electricity from bagasse and wastes. In the future case, the ethanol production includes sugarcane milling, juice clarification, pretreatment and hydrolysis of bagasse, fermentation and purification of ethanol; as well as the co-production of sugar from sucrose and electricity from wastes. In both cases 48% of the sucrose is used to produce ethanol, and 52% is for sugar co-production. The major difference between the two cases is the use of bagasse, in the base case completely for electricity generation, and in the future case mainly for ethanol production. Only is the lignin from bagasse is used together with wastes for electricity generation in the future case. Since the production and disposal of the car is outside of the system boundaries, no waste management and recycling are involved.

2.3. Data sources and software

Data used in this study are obtained from different sources. Agriculture data are obtained from de Macedo et al. [23], or estimated using the methods in report on agriculture published by

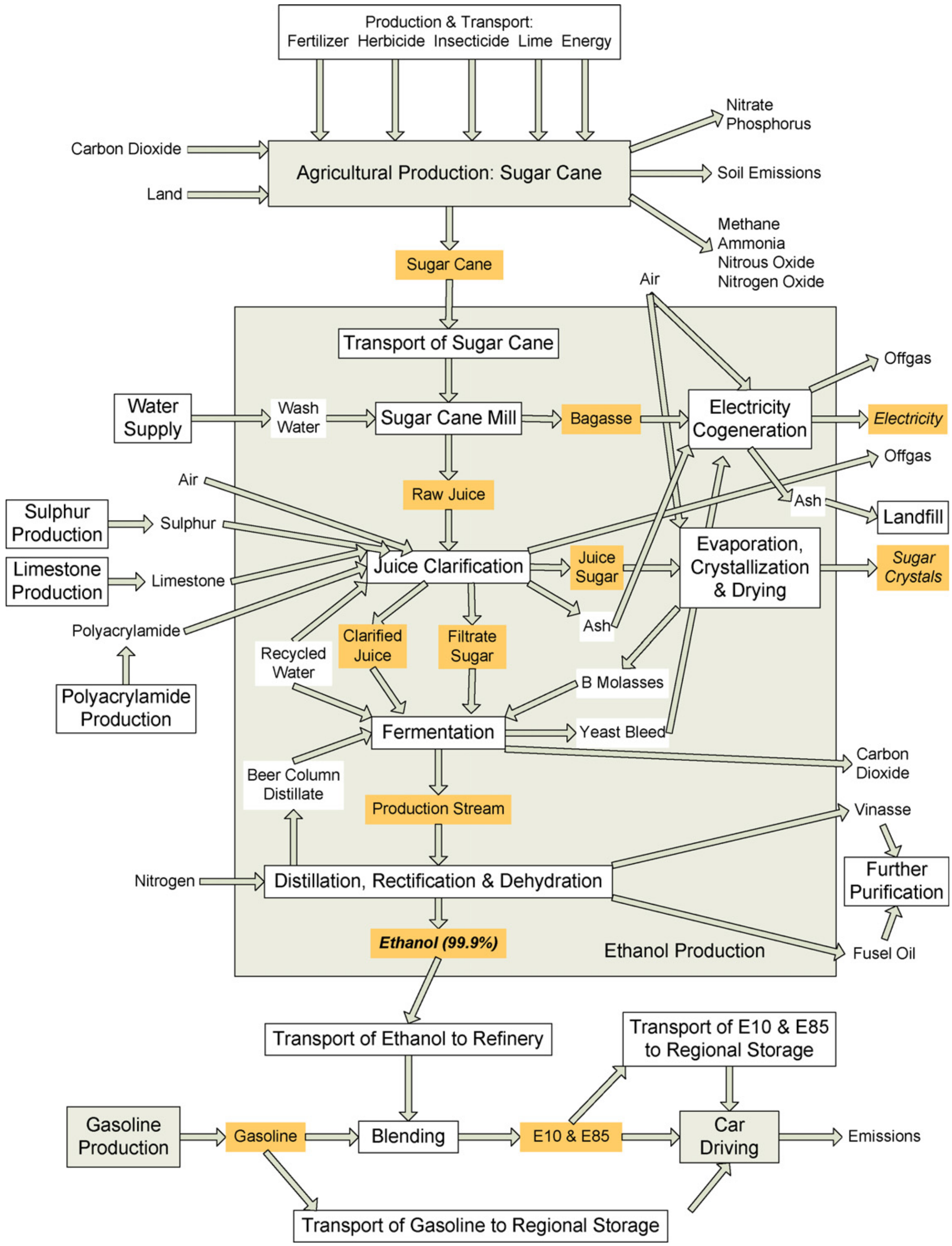


Fig. 1. The life cycle of bioethanol from sugarcane in the base case.

Swiss Center of Life Cycle Inventories (Ecoinvent) [24]. Data on transport of sugarcane are also from de Macedo et al. Process and cost data on ethanol, sugar and electricity productions are produced by Efe [19]. Emissions from capital goods production are from EIPRO database [25]. Gasoline production data are provided by Ecoinvent, and cost data (year 2005) is obtained from Energy Information Administration [26]. Emission data of car driving using gasoline, E10 and E85 are acquired from the reports on emission test of different fuels [27,28]. The completeness of data may differ between sources; therefore one source, Ecoinvent, is used when possible, as this source has a long learning experience and involves a very broad range of processes, around 2630. Data gaps resulting from general data unavailability are filled by making a variety of assumptions as noted below. The software package CMLCA (Chain Management by Life Cycle Assessment) is used for the analysis.

2.4. Key assumptions

In this study, the life time of the ethanol plant is assumed to be 10 years, and the ethanol produced is aimed at a purity of 99.9% in both cases. 48% of sucrose from sugarcane is utilized for ethanol

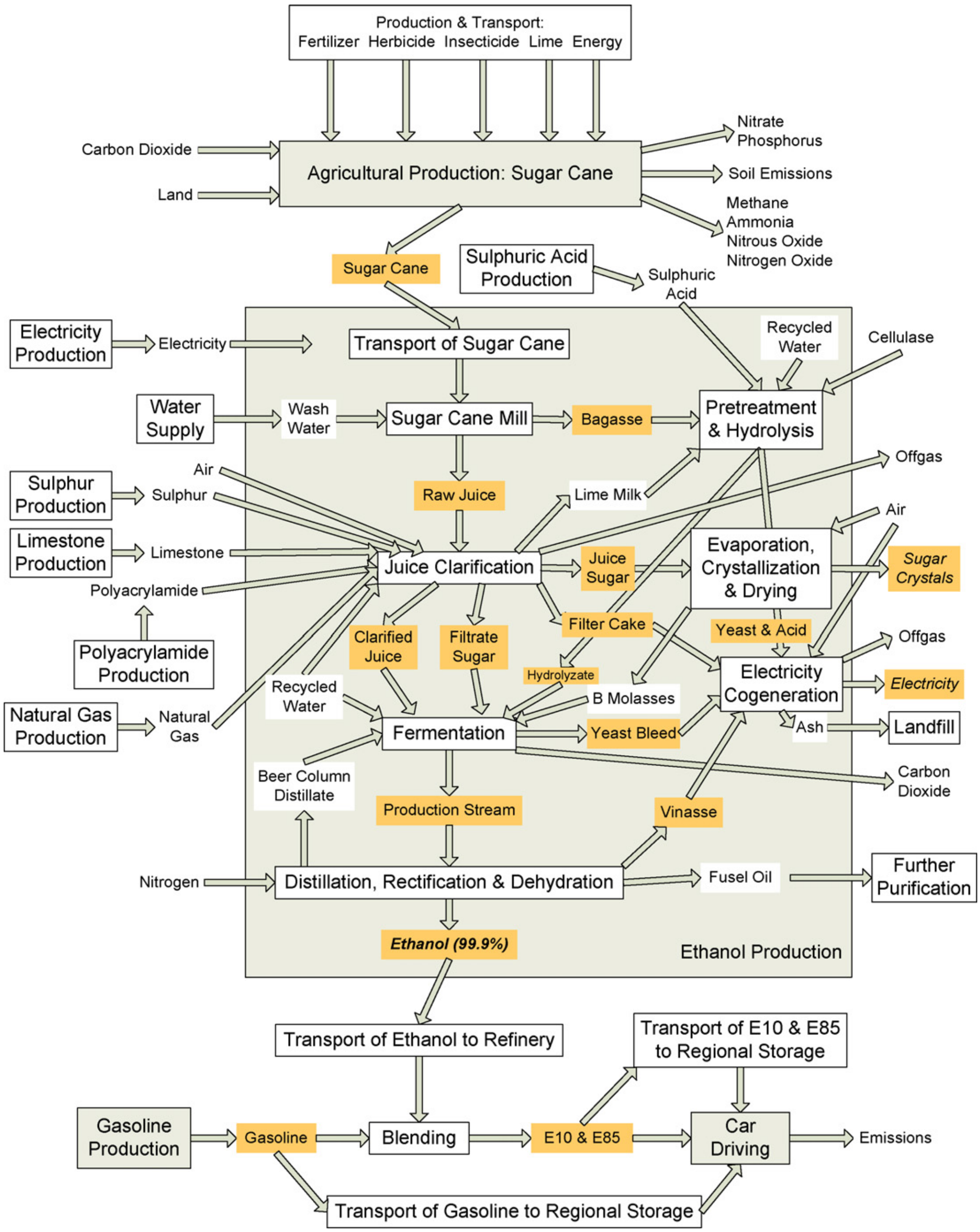


Fig. 2. The life cycle of bioethanol from sugarcane in the future case.

production and 52% is crystallized into sugar crystals [19]. Ethanol production plant is assumed to be located 20 km away from the sugarcane field [23]. Hence the transport distance of sugarcane from the field to the plant is 20 km. The transport of materials and products is by road using lorry with various loading capacities, depending on the needs. 20 km is assumed to be the transport distance of ethanol to the refinery. For the distance between the refinery and the regional storage the value from Ecoinvent is followed (34 km). Therefore for comparison the transport distance of E10, E85 and 100% ethanol to their regional storages is assumed to be 34 km. For gasoline, E10 and E85 emission data are based on a standard test procedure, covering a mix of driving on urban roads and on motorways. For 100% ethanol the emission data is based on assumptions and calculations.

2.5. Allocation methodology

According to the LCA methodology, allocation is required for multi-product processes. In the gasoline life cycle this refers to the oil refinery including drilling oil well, the production of crude oil, the transport of crude oil to refineries, and the refinery of crude oil to produce gasoline, diesel and other co-products. In the gasoline life cycle allocation must be applied to the refinery producing gasoline and other co-products. For gasoline production the allocations were taken as currently implemented in the Ecoinvent database by its designers. In the ethanol life cycle this refers to five sub-processes: sugarcane milling, juice clarification, fermentation, ethanol purification, electricity generation and sugar purification. In these processes economic

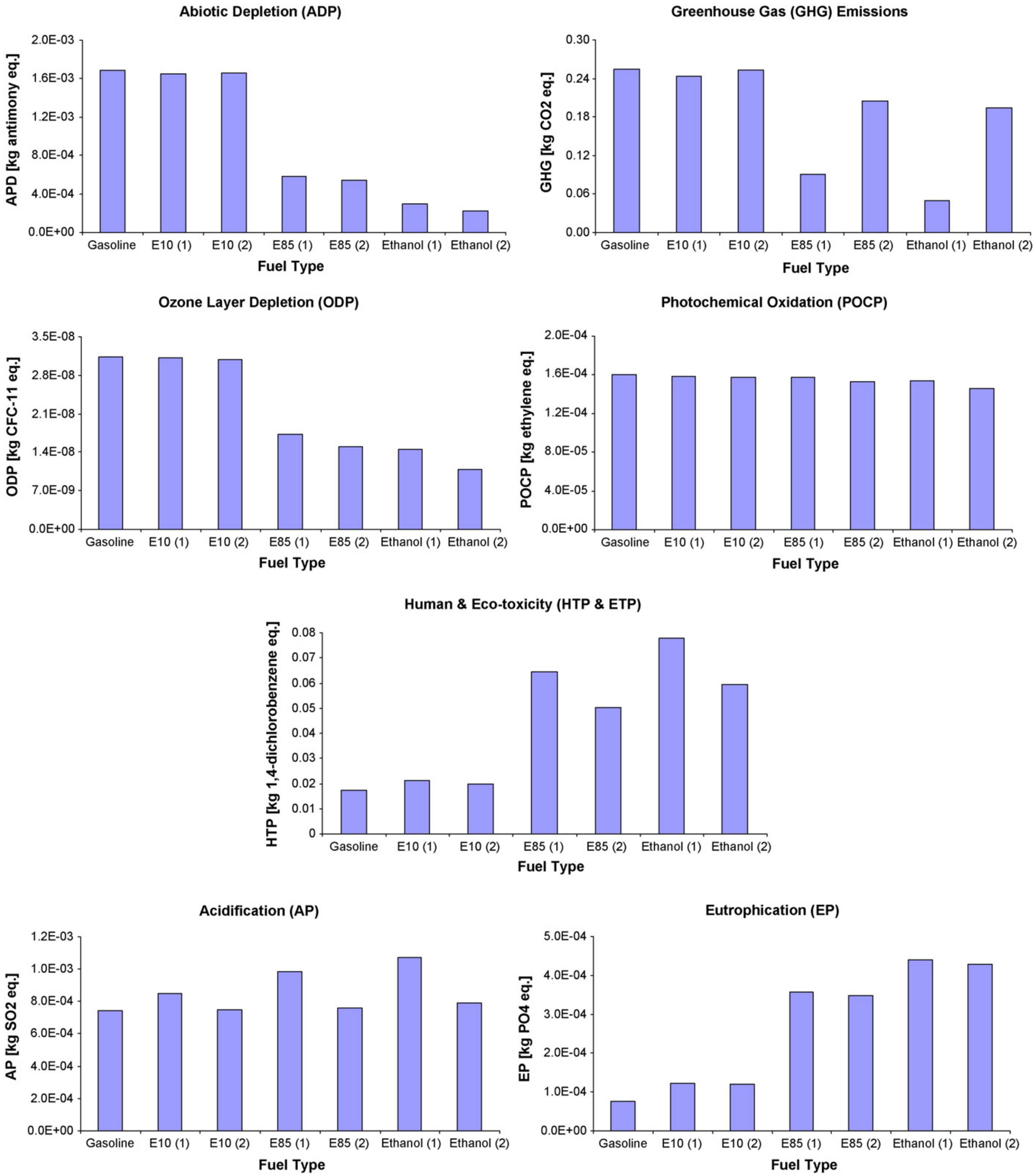


Fig. 3. Overall comparison of the environmental impact of all fuel options.

allocation based on the market value of the process outputs was applied, as specified by the by *Handbook on Life Cycle Assessment* [20].

2.6. Impact assessment

This study mainly focused on the following impact categories:

- Abiotic depletion (ADP)
- Greenhouse gas (GHG) emissions
- Ozone layer depletion (ODP)
- Photochemical oxidation (POCP)
- Human and eco-toxicity (HTP & ETP)
- Acidification (AP)
- Eutrophication (EP)

2.7. Life cycle costing (LCC)

A LCC was conducted with the same system specification, indicating the cost (tax excluded) of 1 km distance driven by a midsize car using gasoline, E10, E85 and 100% ethanol. In LCC a steady-state cost model is used, which means no discounting and depreciation were taken into account. Since the life time of the ethanol plant is assumed to be 10 years, the capital investment is divided over 10 years. Since in the ethanol plant co-produces sugar and electricity in the base case and sugar in the future case, respectively, the fixed capital investment and operating costs were allocated between ethanol and co-products based on their economic values. It is worth noting that in the future case is designed with assumed advanced process technologies, hence all the data on cost is estimated based on the base case.

3. Results and discussion

3.1. LCA

The comparative results of the LCA for all the fuel alternatives in the base and the future case are shown in Fig. 3.

The results show that in the base case the levels of ADP and GHG emissions drastically decrease when replacing gasoline by ethanol fuels, about 83% and 81%, respectively. This is due to the replacement of fossil resources by renewable biological resources. In the future case ADP decreases even more (87%). GHG emissions also decrease, but much less than in the base case (24%) (See below). The reason for the significant decrease in GHG emissions is that the growth of sugarcane takes up a large amount of CO_2, counter-acted only partly by N_2O-emissions from agriculture. For most of the other impact categories, applying ethanol fuels causes a larger environmental impact. The agricultural process contributes largely to human and ecotoxicity, acidification and eutrophication. Ozone layer depletion is much lower for ethanol from sugarcane because it is mainly caused by the methane emission from crude oil production onshore. The POCP level is not significantly changed in both cases. When replacing gasoline by ethanol fuels, emissions causing POCP from natural gas production and crude oil exploitation decrease, but emissions from ethanol storage, fermentation, bagasse treatment and electricity cogeneration increase.

When considering the comparison between the base and future case in terms of environmental impact, in the categories except GHG emissions the future case shows a better performance. More ethanol is made out of the same harvested material: to produce 1 kg of ethanol, only 12.6 kg of sugarcane is needed in the future case, while 30.1 kg is needed in the base case. Regarding GHG emissions, in the base case 77.4 MW of electricity is cogenerated from burning bagasse, while only 18.4 MW is used for the ethanol production and the rest (59 MW) is assumed to be sold to the grid. A significant part of the process emissions from the cogeneration process are allocated to the co-produced electricity. However, in the future case only 13.2 MW of electricity is coproduced from wastes, while 22 MW is needed for the plant; hence 8.8 MW is purchased from the grid. In this case, although more ethanol is produced due to the use of bagasse, net GHG emissions decrease less compared to the base case. This result is different from our previous work on the LCA of bioethanol from corn stover. In the stover–ethanol case, stover is a by-product from corn production. Therefore, a large part of the agricultural emissions and extractions are allocated to corn. When economic value based allocation (stover/corn ratio 0.14/0.86) is applied both less credits (CO_2 uptake) and less penalties (N_2O emission) are allocated to stover. In the case of sugarcane–ethanol, no allocation is required for the agricultural process. Furthermore, sugarcane agriculture is much less intensive compared to corn agriculture in terms of the use of fertilizers, which results in less GHG emissions.

3.2. LCC

Based on the cost data in 2005, the gasoline production cost is calculated to be 0.59 $/kg. Ethanol production costs are 0.30 and 0.26 $/kg in the base case and the future case, respectively. The costs of 1 km driving for all the fuel alternatives in both cases are shown in Table 1.

As a whole, driving with ethanol fuels is cheaper than driving with gasoline due to the low production cost of ethanol from sugarcane. The future case is economically more attractive than the base case. The reason for this is that although in the future case ethanol plant does not co-produce extra electricity, it produces ethanol 2.4 times as the one produced in the base case. As the price of the crude oil is nearly doubled in 2008 compared to the one in 2005 [26], a sensitivity analysis has been conducted with the current oil price. In this analysis all the capital investment and operation costs are assumed to remain same. Moreover, with the growing market of sugarcane–ethanol, the price of sugarcane can increase dramatically. Hence another sensitivity analysis has been done with the assumption of doubling the sugarcane price and taking the 2005 price for crude oil. The 3rd sensitivity analysis has been conducted doubling the prices of both crude oil and sugarcane. The results of the analysis are shown in Tables 2–4.

The results show that in all three scenarios driving on ethanol fuels is much cheaper in both base and future case. The example of E85 fuel shows the upward trend of costs of driving when the prices of crude oil and sugarcane are doubled separately and simultaneously. Furthermore, the differences in fuel economy in base cases are smaller than the ones in future cases. Due to the implementation of advanced process technology in the future case, production costs of ethanol has been brought down significantly.

Table 1
Costs of 1 km driving for all the fuel alternatives.

Case	Gasoline	E10	E85	Ethanol	Unit
Base case	0.0393	0.0388	0.0313	0.0294	$/km
Future case	0.0393	0.0385	0.0282	0.0254	$/km

Table 2
Costs of 1 km driving with double crude oil price.

Case	Gasoline	E10	E85	Ethanol	Unit
Base case	0.0816	0.0784	0.0402	0.0294	$/km
Future case	0.0816	0.0781	0.0370	0.0294	$/km

Table 3
Costs of 1 km driving with double sugarcane price.

Case	Gasoline	E10	E85	Ethanol	Unit
Base case	0.0393	0.0403	0.0483	0.0511	$/km
Future case	0.0393	0.0395	0.0388	0.0390	$/km

Table 4
Costs of 1 km driving with double both prices.

Case	Gasoline	E10	E85	Ethanol	Unit
Base case	0.0816	0.0799	0.0572	0.0511	$/km
Future case	0.0816	0.0790	0.0472	0.0383	$/km

4. Conclusions and recommendations

From the LCA results it can be concluded that in terms of abiotic depletion, GHG emissions, ozone layer depletion and photochemical oxidation ethanol fuels are better options than gasoline, while gasoline is a better fuel where human toxicity, ecotoxicity, acidification and eutrophication are concerned. The future case is promoted due to the use of bagasse to enhance the production efficiency of ethanol; in this study to produce 1 kg of ethanol 30.1 kg of sugarcane is needed in the base case, while only 12.6 kg is needed in the future case. When GHG emissions are concerned, however, burning bagasse for electricity generation (base case) is a much better option than converting bagasse to ethanol (future case); while in all the other aspects the results are better for the future case. The overall evaluation of these fuel options depends on the importance attached to different impacts.

The results of LCC indicate that driving with ethanol fuels is more economical than gasoline, and the future case is economically more attractive than the base case, which has been the driving force for the promotion of advanced technologies converting bagasse to ethanol. Nevertheless, the outcomes depend very much on the assumed price for crude oil, which was considered high in the year of 2005. In the year of 2008 the oil price is nearly doubled compared to 2005, which makes driving on ethanol fuels even more economical. In LCC a steady-state cost model was used and only the production cost was taken into account, hence it can provide a first indication on the economic feasibility of the process. In the real market the prices of fuels are very much dependent on the taxes and subsidies.

In order to achieve an overall evaluation of the environmental impact of different fuel options, weighting factors attached to different impact categories need to be established. As weighting is a rather arbitrary step, we have not attempted it here.

It has to be kept in mind, that the LCA methodology as it stands cannot capture all the relevant impacts. Land and water use and issues related to indirect land use changes and competition with food products do not fit well into the LCA-framework but require a broader approach. Furthermore, technological development in both agriculture and ethanol production can help lowering both the environmental impact and the prices of the ethanol fuels, especially for the future case.

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